Precision Inertial Navigation System: Challenges for Future

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Abstract

Autonomous Precision Inertial Navigation Systems (PINS) for the future need high quality inertial sensors (accelerometers and gyros) and very accurate gravitation compensation. The development of atom interferometers (AI) using laser light pulse provided a new technique for unprecedented accuracy inertial sensing. AI based sensors provides high sensitivities to inertial forces with accuracies superior to all conventional sensors known till now. This technique uses cold atoms as identical drag-free test masses, unlike conventional inertial sensors based on macroscopic test masses, and the de Broglie wave associated with each atom is then utilized to perform interferometric measurements. Laser cooling techniques are used to achieve the required velocity (wavelength) control for the atom source. The accuracy of AI based sensors are; Gyro: $<10^{-7}$ deg/hr, Accelerometer: $< 10^{-10}$g, Gradiometer : $<10^{-11}$g/m and Navigation accuracy : < 5 m/hr class system.

This paper addresses the principles and technical benefits of atom-wave interferometer-based inertial sensors. The components of AI based sensors for laboratory set up and scope of miniaturization for air borne testing and flight applications is also discussed.

Keywords: Atom Interferometery (AI), Laser Cooling, Inertial Sensors, Precision Inertial Navigation System (PINS).

1 Introduction

Presently Inertial Navigation Systems are compensated for gravitational acceleration using approximate Earth gravitation models. Even with elaborate model based gravitation compensation, the navigation errors approach upto several hundred meters/hour. The only solution is to measure gravitation gradient tensor and integration to arrive at accurate gravitation compensation onboard. Additionally, next generation inertial navigation sensors can reduce the dependence on external aids such as GPS etc.

Atom interferometry is nowadays one of the most promising candidates for ultra precise and ultra-accurate measurement of inertial forces on ground or for space. It first transfers an atom into different energy states, and with this two spatially separated matter waves are associated. These single waves then propagate on different paths and the beams interfere when they are recombined [Kasevich, M. and Chu, S,1992]. Enrico Fermi realized the first matter wave interferometer using slow neutrons in 1947. A few years later the first experiment on matter wave interferometry with electrons was demonstrated. In 1991, atom interference techniques were used in proof-of-principle to measure rotations and accelerations[Kasevich, M. and Chu, S., 1991]. Many theoretical and experimental works are reported to investigate this new kind of inertial sensors.

Devices using atom interferometry were recently improved significantly by the methods of laser cooling and trapping of atoms. In 1997, Nobel prize in Physics was given for laser cooling, where laser light is used to cool atomic vapors to temperatures of $\sim 10^{-6}$degK. After this, the experimental techniques to manipulate cold atoms have improved significantly leading to a much higher coherence level of the atoms and higher sensitivity of measurements. Some of the recent works on AI based sensors have shown very promising results comparable to other kinds of sensors, for both angular rate and acceleration measurements[Kohel, J. M., Yu, N., Kellogg, J. R., Thompson, R. J., Aveline D. C. and Maleki, L. , 2004, Fixl J.B., Foster, G.T., McGuirk, J.M. and Kasevich, M.A, 2007].

From performances on ground, one can expect unprecedented sensitivity in space, leading to many mission proposals since 2000 [Fixl J.B., Foster, G.T., McGuirk, J.M. and Kasevich, M.A, 2007]. This technology is now mature enough that several groups are developing instruments for practical experiments: in the field of navigation and fundamental physics (gradiometer for the measurement of G, gravimeter for the watt balance experiment, interferometer for the measurement of fine structure constant) [G. Bagnasco, R. Bingham…., 2001].

2 Why atoms as test masses?

The key characteristics of AI based inertial sensors include long term stability, intrinsic calibration, immunity to environmental perturbations, high sensitivity and robust operation. These advantages emerge from the following attributes :

- Atomic-proof mass: Atoms are used as test masses instead of macroscopic 'proof mass' in conventional sensors. This insures that the material properties of the proof mass will be identical from one instrument to another.
- Atom is in a near perfect inertial frame of reference (no spurious forces).
- Laser/atomic physics interactions determine the the relative motion between the inertial frame (defined by the atom deBroglie waves) and the sensor case (defined by the laser beams).
- Laser distance measurements : Since distances are measured in terms of wavelength of a laser (whose frequency is stabilized to an atomic resonance), the acceleration measurements are intrinsically calibrated. This guarantees long term stability, accuracy and precision.
- No moving parts: With the exception of the atoms, there are any moving parts in these designs.

3 Principle of Atom Interferometry

The de Broglie wavelength of an atom matter-wave is λ_{dB} = h/Mv, where h is the Plank constant, M the atom mass and v its velocity. These matter waves are used to perform as interferometer. When an atom absorbs or emits a photon momentum must be conserved between the atom and the light field. Absorption and stimulated emission of photons can change the momentum of the atom by ħk and, simultaneously, its internal state. There are several methods for matter wave beam splitting and mirroring. The most commonly used set up uses two photon Raman pulses to impart momentum to an atom beam.

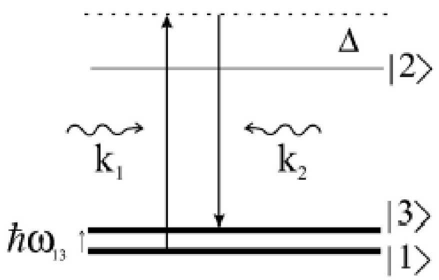

Figure 1: Two photon Raman transitions

Consider a two photon transition as shown in fig 1. Two counter-propagating laser beams are used to induce atomic transitions. The first laser pulse **k1** excites the atom into a virtual level (dotted line in fig 1) which is detuned from the nearest atom state |2> by Δ to avoid spontaneous transitions. This emission results in a momentum kick of the atom by ħk1. A counter propagating second laser pulse k2 ≈ −k1 then induces an emission which leaves the atom in state |3>, higher than the initial state |1>. The total momentum received by the atom is thus ħ(k1−k2) ≈ 2ħk1.

By precisely timing the duration of the laser pulses, a complete transfer from one state(|1>) to other (|3>) is possible in case of a π pulse and a 50/50 splitting between the two states in case of a π/2 pulse.

Fig 2 shows how a sequence of three such Raman pulses is used to split, redirect and recombine an atom while simultaneously changing its internal state. At the end of this sequence the fraction of the atoms in one of the states is detected. Inertial forces manifest themselves by changing the relative phase of the de Broglie matter waves with respect to the phase of the driving light field, which is anchored to the local reference frame. The physical manifestation of the phase shift is a change in the number of atoms in, excited or ground state after the interferometer pulse sequence [Kasevich, M. and Chu, S,1991,1992].

When a π/2 pulse is applied to the atomic beam entering the interaction region, it leaves half of the atoms of the beam in their initial state and their initial velocity but alters the path of other half of the atoms and therefore acts as a beam splitter. After some distance, a π pulse is applied and it interchanges the internal states and momenta of the two beams and thus acts as a mirror. Finally another π/2 pulse joins the two beams forming a matter-wave Mach-Zehnder type interferometer [Kohel, J. M., Yu, N., ….., 2004]. So half of the atoms in either of the two atomic states |1> or |3> come from each arm resulting in an interference pattern in the number of atoms in either state. The number of atoms in any state can be measured using a probe laser and counting the atoms on a fluorescence screen.

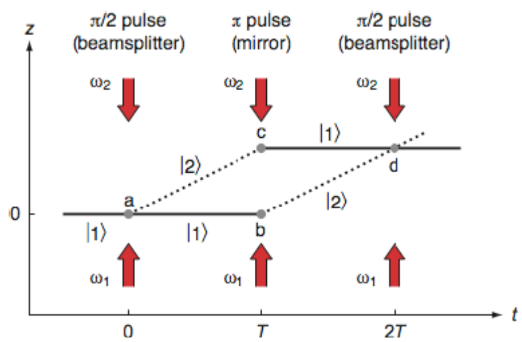

Figure 2: Light Pulse atom interferometer

4 Inertial measurements with atom interferometers

Atoms are first collected and cooled by lasers into a small cloud in a magneto-optic trap (MOT). The MOT, consists of three pairs of counter-propagating laser beams along three orthogonal axes centered on a non-uniform magnetic field, collects up to 10^9 atoms from a beam or a background vapor. After these atoms are collected, further laser-cooling brings the atoms' temperature down to 10-20μK. Laser cooling does not only reduce the mean drift velocity of the atoms but also increases their coherence. Indeed, if all the atoms could be controlled to exactly the same velocity then they behave as a single coherent wave whose wavelength is the de-Broglie wavelength.

The cold atoms are launched vertically by introducing a slight frequency shift between pairs of lasers to create a moving "rest frame" for the atom ensemble. This so-called "atomic fountain" enhances the available interaction time with the atoms. The atom interferometry is then performed during the subsequent free fall of atoms in the atomic fountain. During free fall, the relative motion is between the inertial frame (defined by the atom atom waves) and the sensor case (defined by the laser beams).

4.1 Acceleration measurement

In the atom interferometer, if the 3 light pulses of the pulse sequence are only separated in time, and not separated in space (i.e. if the velocity of the atoms is parallel to the laser beams), the interferometer is in a gravimeter or accelerometer configuration[G. Bagnasco, R. Bingham,…..,2001].. In a uniformly accelerating frame with the atoms, the frequency of the driving laser changes linearly with time at the rate of $-\mathbf{k}_{\mathbf{eff}}$.at because of the Doppler Effect. The phase shift arises from the interaction between the light and the atoms and can be written as $\Delta\varphi \equiv \varphi_1(t_1) + \varphi_2(t_2) + \varphi_3(t_3)$; where $\varphi_i(t_i) = \int\delta(t)dt$ is the phase of light pulse at time t relative to the atoms and δ is the laser detuning (the difference between the laser frequency and the atomic transition frequency). Since the photon energy is related to the laser wavelength and hence its frequency, the atomic transition can be driven by laser light only if the laser frequency is equal to the atomic transition [G. Bagnasco, R. Bingham,…..,2001]. Hence δ should be very low as possible.

If the atom is in initially in state |1> then the measurement of number of atoms in state |3> at the end of interferometric sequence allows determination of $\Delta\varphi$. If the laser beams are vertical, then the resulting phase difference accumulated along the atom interferometer paths is given by

$$\Delta\varphi = - k_{eff} \, . \, aT^2 \qquad \textbf{(1)}$$

whenever a constant acceleration a is present and $k_{eff} = k2 - k1 \cong -2k1$ and T is the temporal separation between two optical pulses[Yu, N., Kohel, J.M., Kellogg, J.R. and Maleki, L.,2006]. This phase shift does not depend on the atomic initial velocity or on the mass of the particle.

4.2 Gravity Gradiometer

Local mapping of the earth's gravitational field has important applications in navigation, geodesy, and oil and mineral exploration. Each of these applications requires the gravity-sensing instrument to be mounted on a moving platform, which is subject to accelerations originating from the platform's motion. These accelerations render high-resolution measurements of the acceleration due to gravity difficult, as platform accelerations are in principle indistinguishable from gravitationally induced accelerations. A well-established means of circumventing this problem is to measure gradients in the gravitational field by comparing acceleration measurements at two locations separated by a fixed distance.

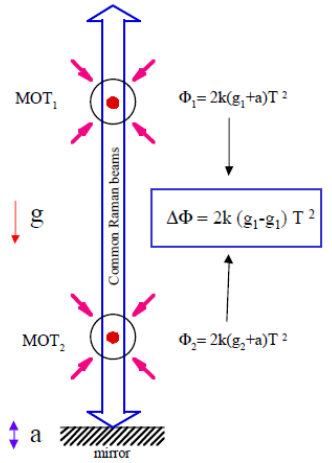

Figure 3 : Illustration of two magneto-optical traps and the configuration as a gravity gradiometer.

Two independent vertically separated ensembles of atoms from two MOT's on vertical ballistic trajectories are made to perform the interferometer. (fig. 3). A laser beam whose propagation vector passes through both the ensembles, simultaneously records the acceleration of each ensemble. Gravity gradient measurements are made by taking difference of the two acceleration measurements. Since the acceleration measurements are made simultaneously at both positions, many systematic errors including platform vibration, cancel as a common mode noise and uncertainties are effectively cancelled [Kohel, J. M., Yu, N., …..,2004].

Gravity gradiometer can be used for Precision autonomous navigation in long duration missions, aircraft navigation and submarine navigation applications where external aiding is not possible. In addition to that, gravity gradiometer is highly useful for Earth science studies like:

- Global gravity mapping
- Oil & Under ground water exploration
- Sub surface mass distribution of earth and planets and temporal monitoring of its dynamical processes
- Successful assessment of earthquake and volcanic hazards.
- Significant advancement in the knowledge of the Solid earth & the Oceans
- Understanding the planetary inner structure and dynamics
- Changes in ocean currents and ice sheets

4.3 Gyroscope

An atom interferometery based gyroscope called atom gyroscope measures the rotation using Sagnac effect. The rotation induced phase shift (Sagnac Phase) between two interfering paths of an atomic wave will be zero in the absence of any rotation[Gustavson, T., Bouyer, P. and Kasevich, M.,1997] . Because of finite phase shift, occurring due to rotation, the atom would make a transition after the pulse sequence is applied in the interferometer.

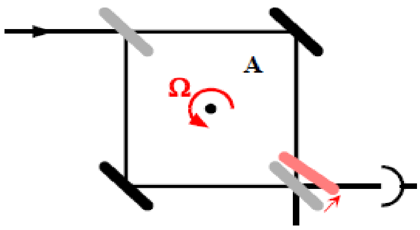

Figure 4: Sagnac effect using atom waves

For rotation measurement, the laser beams of the interferometer) in Mach-Zenhder configuration in fig.2 is separated in space (i.e. the atomic velocity is perpendicular to the direction of the laser beams transition [G. Bagnasco, R. Bingham,…..,2001]. For a Sagnac loop enclosing area **A**, a rotation Ω produces a shift:

$$\Delta\varphi = (4\pi/\lambda v)\ \Omega.A \ = 4\pi\ (mA/h).\ \Omega \qquad \textbf{(2)}$$

where λ is the particle wavelength, m is atom mass and v its velocity.

Because of the finite mass of the atom and wavelength of atom waves are smaller than light wavelength, the inherent inertial sensing sensitivity of atom interferometer is more than a photon-based system by a factor of $mc^2/\hbar\omega \sim 10^{11}$ (*m* is the particle mass, ω the photon frequency). This ratio is simply the ratio of relativistic energies *'mc*^{2} for the atoms and ħω for the light. And since atoms have properties such as mass and electrical polarizability, they can measure things which cannot be detected with an optical interferometer.

5 Experimental apparatus / Laboratory model

The laboratory model of AI based sensors consists of two separate vacuum chambers, each of which supports an atomic fountain [Kohel, J. M., Yu, N., …..,2004]. Atomic physics package is the major component of AI and it includes the vaccum chamber, MOT's, atom source and manipulation of the atoms waves for interferometry. The laser system is another major component and it includes the laser and optics subsystems for controlling the laser parameters and enabling the phase lock for the required frequency stability needed for atom collection, cooling, interferometry and detection. Electronics and Control package precisely controls all laser frequencies and amplitudes, applied magnetic fields and generation of precise timing sequences of the optical pulses.

Transportable models of AI based inertial sensors have additional design constraints to accommodate the requirements of size, weight, power consumption and robustness. Additionally the instrument must be capable of stand-alone operation in a remote location. For space-based application, size and weight are major constraints and requires further miniaturized components which are space reliable also.

Laboratory models are already developed in laboratories world wide to demonstrate the technology of AI based inertial sensors. Transportable models are also built as part of R&D projects under ESA, NASA(JPL), DARPA etc. and they have proved the high accuracy inertial sensing in air borne and submarine models. In an effort to develop a system beyond the laboratory setup, it has been reported that space borne modularized set up are under finalization in laboratories world wide using miniaturized technologies. 'Hyper' mission of ESA (proposed in late 2000) will be the first satellite mission using atom interferometry based inertial sensors only for navigation and control of spacecraft.

The ultra cold atoms (approximately 10µK) are initially extracted from a low-pressure background vapour and loaded into a magneto-optic trap (MOT). After turning off the magnetic trapping fields, the atoms are launched vertically using moving optical molasses to form an atomic fountain. Three pulse sequences (π/2- π- π/2) spaced by time, T is applied for Atom Interferometry. The atomic wave function after the interferometry is a superposition of the two states containing information about the inertial forces impressed to the atoms and any other dephasing effect. The relative populations of the two states are measured for the interferometric read out of the phase measurements.

The major elements of a laboratory model of AI based inertial sensor are the following:

Vacuum Chamber: The experiment is performed in an Ultra High Vacuum environment ($\approx 10^{-9}$ mbar) in order to minimize problems related with collisions with thermal background gases. The system includes a pumping system to keep the whole apparatus under vacuum (turbo pump (75l/s capacity) as main pump and also auxiliary pumps for occasional use. It also includes a trap chamber for trapping the atoms, interferometer tube for carrying out the interferometry, detection chamber installed between the trap chamber and the interferometer tube and atomic source (Rb getters) which are connected to an electrical feed-through so that a current control from the outside is possible.

Computer Control system: The timing of the experimental sequence must be controlled with a precision better than 100 μs for most of the experimental actions. A much higher resolution is needed for the interferometer pulse sequence (100 ns) for higher accuracy measurements. A software control system is needed for programming the control system in several ways to optimize the experimental sequences of light pulses in required width and time.

Atomic fountain apparatus: This provides a well-defined source of laser-cooled atoms for the interferometer. It also allows the detection of the final state of the atoms at the output of the interferometer. This is done by trapping and cooling a sample of ^{87}Rb atoms with a magneto-optical trap (MOT) and by launching them upwards with a moving optical molasses.

Optical system for implementing the actual light pulse interferometer, including the phase-locked diode lasers and the equipment for controlling the frequency and timing of the Raman pulses. Other components are the Raman beam optics and the magnetic shielding of the measurement region.

Vibration Isolation: The atom interferometer measurements are relative measurements; in the sense that the motion of atoms are being measured with respect to the phase of the driving light field. Any change in the relative paths of the two beams due to external vibrations will be seen as a spurious interferometer phase shift and noise in the measurement. To prevent this, vibrations have to be reduced to a level where the resulting phase shifts are much smaller than 1 rad. Vibration isolation system is an important component of AI based sensor development, which allows the large interferometer pulse separations essential for obtaining required measurement accuracy and precision [Yu, N., Kohel, J.M., Kellogg, J.R. and Maleki, L.,2006].

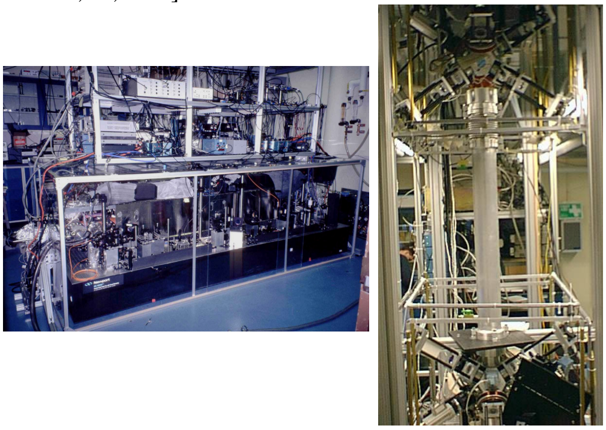

Figure 5a: Laboratory model of AI gyroscope(Left) and gravity gradiometer (Right) at Stanford UIniversity

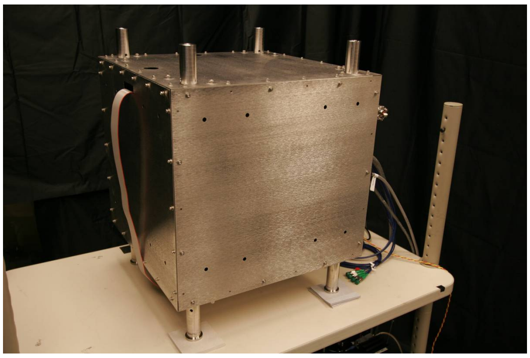

Figure 5b: Transportable model of AI based sensor developed by Stanford University to measure gravity gradient, rotation and linear acceleration along a single axis.

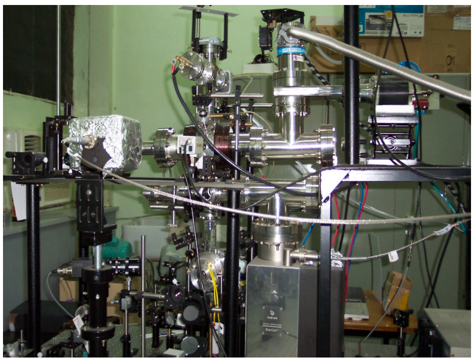

Figure 6a . Experimental Set-up for Rb^{87} at RRCAT, Indore

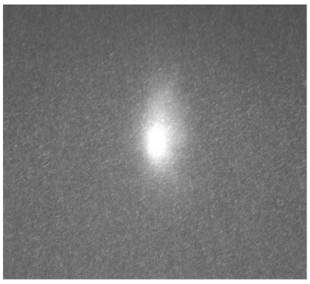

Figure 6b . Rb^{87} atoms in MOT at RRCAT, Indore.

For future precision inertial navigation system using AI sensors, activities are already initiated in IISU. As a first step laser cooling laboratory will be established using double MOT and gravity gradient measurements will be made. After capturing the technology, transportable model and later space model will be realized.

6 Space model development

Recently the combination of well-established tools for atom cooling and manipulation with state-of-the-art micro fabrication technology has led to the development of atom chips to confine, cool and manipulate cold atoms[Alexander Cronin,2006]. Recent works reported that robust cooling methods are possible using RF potentials [Hofferberth, S., Lesanovsky, I., Fischer, B., Verdu, J. and Schmeidmayer,2006] which allow easy production of cold atoms. This powerful tool for manipulating cold atoms is complementary to magnetic trapping also. The beam splitters are used to split atom waves in a coherent way. This capability is also achieved [Schumm, T., Hofferberth, S., Anderson, L.M., Wildermuth, S., Groth, S., Bar-Joseph, I., Schmeidmayer, J. and Kruger, P,2005] in an atom chip, based on radiofrequency (RF) currents. Recent publications shows that RF induced potentials could lead to further applications and are of particular interest with regard to miniaturization of atom-optics devices. Miniaturized devices also shown to be capable of trapping and guiding ultra cold atoms on a micro scale. A compact beam splitter (coherently splitting atom waves) and trapping/confinement based on RF currents is demonstrated in [Alexander Cronin,2006, Hofferberth, S., Lesanovsky, I., Fischer, B., Verdu, J. and Schmeidmayer,2006]. Recent literatures reveal the quantum of work going on to establish miniaturized components for Atom Interferometery. Hence, the realization of next generation of inertial sensors using AI technology is not far.

7 Conclusions

The accuracy and precision of current atom-interferometric inertial sensors rival state-of-the-art conventional devices using artifact-based test masses. It is important to develop sensors and system based on AI as it is the most promising future technology. Other advanced countries have already developed these sensors and systems and working on miniaturization of the same. It is possible to achieve less than 5m/hr class navigation system using AI based accelerometers, gyroscopes and gravity gradiometer. It is a challenging task to develop compact and transportable AI sensors which are robust and low cost with reduced weight, than the conventional sensors.

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